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Petrodiesel Blend Study for Biodiesel Production from *Bauhinia variegata* Seed Oil

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Abstract

The present study focuses on the microwave-assisted transesterification (MAT) employed in *Bauhinia variegate* (BV) biodiesel production in a shorter reaction time with a better yield. The oil was extracted and characterized for physiochemical, fatty acid composition, and Fourier transform infrared analysis. The lower acid value (<2) indicated that the oil can be processed to the transesterification process. MAT was optimized for maximum biodiesel production using the statistical tool with maximum biodiesel yield of 96.83% at the optimum condition of oil to methanol ratio – 1:7 (v/v), catalyst concentration – 1 (wt%), power – 450 W at 10 min. The result was well in agreement with the physicochemical properties of ASTM D6751 standard prescribed limits. Nevertheless, the BV diesel physiochemical properties were higher than that of petrodiesel. It is then blended with petrodiesel to investigate the calorific value, density, kinematic viscosity, flash point, cloud and pour point. It was found that up to 20% biodiesel blending gives close results with petrodiesel properties. From experimental results, the MAT process was efficient in a shorter time technique for BV biodiesel production. This beneficial approach leads to reducing the production cost of biodiesel in a continuous mode.

Keywords

biofuel, transesterification, optimization, fuel properties, ASTM standards

1 Introduction

Petroleum based resources are a major contribution to the energy sector and the burning of coal cause the greenhouse effect, change in climatic conditions, and air pollution [1]. When the dependence on fossil fuel is reduced, the presence of carbon dioxide in the environment reduces eventually [2]. Hence, the search for renewable, economically feasible, and sustainable sources remains of top importance for research to remove and/or reduce environmental related issues. Biodiesel is one of the alternative fuels in order to reduce carbon emissions compared to petroleum-based fuels [3]. It can be produced from vegetable oil triglycerides (TG) via the transesterification process whereas alcohol is used as an esterification agent [4]. The most commonly used alcohol for producing biodiesel is methanol. The Fatty acid esters obtained from oil when reacted with methanol, form as fatty acid methyl esters (FAME). In an industry, a homogeneous, alkali-catalyst is used in the transesterification process commonly, due to faster kinetics and economic feasibility [5]. Renewable biodiesel is produced from many feedstocks and 75% of the total producing cost lies in fresh feedstock and process optimization [6, 7]. This is around 1.5 times more than the commercial diesel (fossil fuel) produced [8] and it would be used as upcoming vehicle fuel because of its oxygen-bound nature, renewable and sustainable energy source [9, 10].

Non-edible oil sources are an excellent alternative for edible vegetable oils. Since biodiesel, manufactured from vegetable oils is highly viscous, with a lower calorific value, that leads to increasing the consumption of fuel volume [1, 11] Various types of non- edible seeds (Castor, Mahua, Karanja, Linseed, Neem, etc.,) are used for biodiesel production [12] along with *Bombax ceiba* [13], *Terminalia belerica* [14], and *Moringa oleifera* [15]. In the current research, a potential feedstock i.e., *Bauhinia variegate* (BV) seed oil is employed to produce biodiesel. BV grows mainly in the tropical region and is generally known as poor-man's orchid or mountain ebony tree [16].

This is used as an ornamental plant and is also found on roadsides, gardens, and parks [17]. *B. variegata* plant, all parts have potential medicinal uses, particularly the

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extract of leaves is beneficial for antimicrobial, antifungal, antimicrobial, antitumor, analgesic, and antipyretic activities [18–20]. *B. variegata* seeds contain a significant amount of oil, proteins, mineral and vitamins. *B. variegata* is a hardy tree species widely distributed in tropical and subtropical regions and can grow in marginal or degraded lands with relatively low water and maintenance requirements. Hence, cultivation of this non-edible feedstock for biodiesel production could be expanded on non-agricultural lands without significantly impacting food security or local biodiversity [17]. The transesterification reaction comprises converting oil fatty triglycerides into FAME with the help of alcohols (generally methanol or ethanol) in the presence of catalyst where glycerol is produced a by-product [11]. Various techniques like conventional heating, supercritical methanol, enzymatic catalysis, and microwave-assisted transesterification (MAT) are used to produce biodiesel [19–21]. Among all the techniques MAT is energy-efficient due to its accelerated reaction kinetics rate and high product selectivity; microwaves are preferred over conventional heating methods [22–24]. Due to the mechanism of dipolar rotation, interfacial polarization, and ionic conduction, localized and rapid superheating occurs in the reaction vessel. This tends to the formation of energy (heat) by an interaction between reaction molecules at higher in a shorter time [7]. This effect can be called an "instantaneous localized superheating". The localized superheating observed during microwave irradiation arises from dielectric heating mechanisms involving dipolar polarization and ionic conduction. During scale-up, continuous-flow microwave reactors with optimized field distribution and controlled hydrodynamics can maintain efficient volumetric heating while minimizing macroscopic thermal gradients in the reaction medium [1, 23].

This has been attempted for the first-time using MAT biodiesel produced from *Bauhinia variegata* seeds and blending with petrodiesel in different ratios. The blending study was carried out to utilize the oxygen content present in the biodiesel which tends to complete the fuel combustion. Moreover, it reduces carbon monoxide and other hydrocarbon (HC) emissions with lower sulphur content and zero soot [25]. In addition, in this work, we attempted to find a better biodiesel petrodiesel blend with ASTM standard fuel properties. This could result in a fuel that combines the benefits of diesel and biodiesel.

2 Materials and methods

2.1 Seed material preparation

Bauhinia variegata seeds were collected (Chennai, India), cleaned and dried in an oven at 62 °C for moisture content removal. The dried seeds were grounded and screened using (ASTM-mesh No. 30) in order to obtain a particle of approx. 0.59 mm (uniformly). Further, the screened powder was stored at 4 °C until the extraction process.

2.2 *Bauhinia variegata* seed oil extraction

A Soxhlet apparatus was used for extracting oil from seed powder (10 g) of *Bauhinia variegata,* using about 250 mL n-hexane. The condensed solvent was recycled and the process was repeated until the entire oil from the solid matrix is done [26].

2.3 Microwave-assisted transesterification

The transesterification process was employed with the desired amount of *Bauhinia variegata* oil (BVO) mixed with alcohol (methanol) placed in a microwave reactor (Raga Tech, Pune India) with a constant frequency of 2.45 GHz. KOH was used as a catalyst for transesterification process. Microwave power, concentration of catalyst, oil to methanol ratio and time are varied (as per response surface methodology (RSM) design). The liquid and solid phases of the mixture was fractionated using a separating funnel. Three layers were formed comprising of methyl ester in the upper layer, glycerine in the middle, and catalyst is the lower layer. The biodiesel was separated by draining out the catalyst and glycerine from the funnel. Biodiesel may contain traces amount of catalyst as well as methanol which were removed using centrifugation and distillation (at 70 °C), respectively. Further nitrogen purging was employed to remove the alcohol (if present) in the biodiesel. The obtained biodiesel yield of each run was calculated by Eq. (1).

$$BY = \frac{m_B}{m_o} \times 100\% , \tag{1}$$

where BY – biodiesel yield, m_B – mass of biodiesel, m_o – mass of oil.

2.4 Characterization of oil

Physicochemical properties, fatty acid composition were determined and Fourier transform infrared (FTIR) analysis was carried out. Fuel characterization of BV biodiesel and BV biodiesel–petrodiesel details were performed using the following standards and their corresponding equipment details given below in Table 1 [27–32].

Table 1 List of equipment used in this study

Analysis/Property	Equipment	Manufacturer
Kinematic viscosity (ASTM D445-24) [27]	Automatic viscosity analyzer, Herzog – HVM 472	PAC, USA
Density (ASTM D4052-22) [28]	Digital density meter, 4500M	Anton Paar, UK
Flash point (ASTM D93-26) [29]	Automatic PMC flash point tester, APM-8	Tanaka, Japan
Calorific value (ASTM D240-25) [30]	Automatic basic calorimeter, C2000	IKA, UK
Cloud point (ASTM D2500-23) [31]	Automatic cloud and pour point analyzer, MMP 5GS	PAC, USA
Pour point (ASTM D97-17b(2022)) [32]	Automatic cloud and pour point analyzer, MMP 5GS	PAC, USA
FTIR	FTIR-spectrophotometer,6600	Jasco, Japan
Fatty acid composition	GC-FID, TRACE-1110	Thermo Scientific, India

2.5 Response surface methodology

Design Expert 13 software, version 13.0.5.0 (STAT-EAS EInc., Minneapolis, USA) was used for Face-Centered Central Composite Design (F-CCD) matrix of MAT process for biodiesel production. The influence of four process variables, viz., oil to methanol ratio, catalyst concentration, time and power were analyzed in order to obtain maximum biodiesel yield (%). Based on the primary experiments the range of process parameters was decided and is given in Table S1. The required numbers of experiments (runs) with different combinations were determined using Eq. (2):

$$N = 2k\left(k-1\right) + Nc\,, \tag{2}$$

where, N is the required number of experiments, k is the quantity of independent factors and Nc denotes the center points available in the design format. The MAT performance was evaluated based on obtaining biodiesel yield (%) of RSM developed experimental sequences. The correlation between the experimental and developed model is analyzed using a second-order polynomial Eq. (3).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \sum_{i=1}^{k} \beta_{ij} X_i X_j + \varepsilon\ \ldots, \tag{3}$$

where Y is the response (biodiesel yield); X_i and X_j indicate independent variables; β_0 is the coefficient (intercept) of the model; β_j, β_{ij}, and β_{ii} and are the coefficients (interaction) of the linear, second-order terms and quadratic, respectively [3, 33]. Based on the experimental values, the significance of the developed model was employed *via* analysis of variance (ANOVA). Three and two-dimensional plots were generated to understand the interaction effect of MAT variables on biodiesel yield. The optimization of MAT variables was performed using Derringer's desired function methodology [34].

The numerical optimization can be used for either one or more goals based on our requirements [34]. In this study, process variables goals were set as 'in range' and the biodiesel yield was set as 'maximum'. In addition to that, each optimum solution given with a desirability value. This value could be in the range between 0 to 1 [35]. According to the desirability value, 1 refers to a highly desirable response and 0 indicates entirely undesirable to perform with lower applicability [8, 26].

3 Results and discussion

3.1 *Bauhinia variegata* seed oil extraction

The BVO yield was determined for every one-hour interval up to 5 h by Soxhlet extraction and the yield was calculated using Eq. (4) [33]. The oil and the solvent were separated using a rotary vacuum evaporator.

$$BVO\ yield\left(\%\right) = \frac{m_o}{m_s} \times 100\,, \tag{4}$$

where m_o – mass of oil, m_s – mass of sample.

The BVO extraction experimental results are given in Fig. S1. It can be seen that the maximum BVO yield was obtained at 4 h and the value was 32.43%. Further increasing the time the yield remained constant. This might be due to attainment of equilibrium [26].

3.2 Physicochemical properties of *Bauhinia variegata* oil

The physicochemical properties of BVO are determined as per ASTM standards, and the results are given in Table 2 [27–32, 36–39]. The most prominent parameters in oil are acid value and free fatty acids [40]. For an efficient transesterification process the free fatty acids and the acid value have to be lower than 1 and 2, respectively. The reaction creates soap buildup instead of methyl esters [41].

From the present study BVO values of free fatty acids (0.65) and acid number (1.30) clearly show that BVO can be treated for the transesterification process. The other properties such as viscosity (31.9 mm^2/s) and thermal properties, such as flash (208 °C), cloud (5 °C) and pour points (7 °C), need to be improved via transesterification to meet the biodiesel specification (ASTM D6751-24) [42].

Table 2 Physicochemical properties of BVO

Properties	Unit	Standard	Value
Kinematic viscosity	mm^2/s	ASTM D445-24 [27]	31.9 ± 0.23
Density	kg/m^3	ASTM D4052-22 [28]	904 ± 0.91
Acid value	mg KOH/g	ASTM D1980-87(1998) [36]	1.3 ± 0.19
Free fatty acids	% mass	ASTM D5555-95(2023) [37]	0.65 ± 0.06
Flash point	°C	ASTM D93-26 [29]	208 ± 0.98
Calorific value	kJ/kg	ASTM D240-25 [30]	38502 ± 2.79
Ash content	%	ASTM D874-23 [38]	0.017 ± 0.08
Carbon residue	%	ASTM D4530-25 [39]	1.1 ± 0.22
Cloud point	°C	ASTM D2500-23 [31]	5 ± 0.13
Pour point	°C	ASTM D97-17b(2022) [32]	7 ± 0.16

3.3 Fourier transform infrared analysis

The FTIR spectrum of BVO is presented in Fig 1. The intense band between the 724 cm^{-1} to 1500 cm^{-1} denotes the presence of many C–H groups. This includes, the cis C=C bending associated at 724 cm^{-1}, –C–O vibration of ester groups detected at peaks of 1145 cm^{-1} and 1226 cm^{-1} and –C–H bending of CH_2 corresponding to the peaks [43] at 1371 cm^{-1} and 1458 cm^{-1}. The large peak at 1740 cm^{-1} is associated with the C=O carbonyl group. The peaks at 2846 cm^{-1} and 2919 cm^{-1} indicates the presence of asymmetric CH_2 and symmetric stretching vibrations respectively [44].

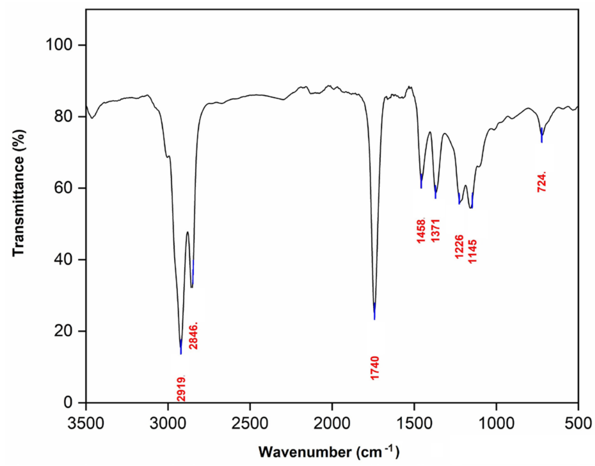

Fig. 1 FTIR spectrum of BVO

3.4 Fatty acid composition

BVO fatty acid composition was analyzed. The gas chromatogram and the results are givenin Fig. 2 and Table 3, respectively. From the results, the presence of fatty acid groups in the BVO is as follows: poly unsaturated fatty acid > saturated fatty acid > mono unsaturated fatty acid. The fatty acid length increases the calorific value and negatively affects the fluid properties. Generally, mono unsaturated fatty acids are preferred to be better in biodiesel. The present oil contains saturated fatty acids and poly unsaturated fatty acids in a higher amount which could be the reason for the maximum kinematic viscosity of the oil. Nevertheless, the presence of saturated fatty acids provides better oxidative stability which helps in a longer

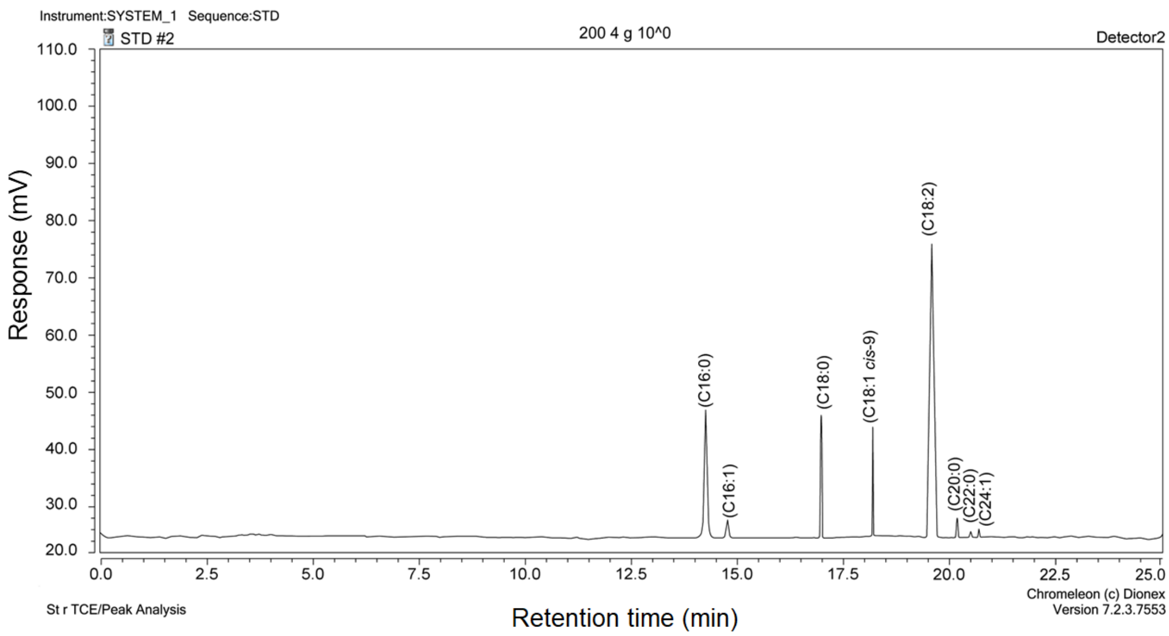

Fig. 2 Gas chromatogram of BVO

Table 3 BVO fatty acid profile

S. No	Fatty acids	Formula	Composition	Type
1	Palmitic acid C16:0	$C_{16}H_{32}O_2$	22.5	SAT
2	Palmitoleic acid C16:1	$C_{16}H_{30}O_2$	0.2	MUFA
3	Stearic acid C18:0	$C_{18}H_{36}O_2$	18.3	SAT
4	Oleic acid C18:1 *cis*9	$C_{18}H_{34}O_2$	13.3	MUFA
5	Oleic acid C18:1 *cis*7	$C_{18}H_{34}O_2$	0.1	MUFA
6	Linoleic acid C18:2	$C_{18}H_{32}O_2$	44.3	PUFA
7	Linolenic acid C18:3 n-3	$C_{18}H_{30}O_2$	-	-
8	Linolenic acid C18:3 n-6	$C_{18}H_{30}O_2$	-	-
9	Archidic acid C20:0	$C_{20}H_{32}O_2$	0.9	PUFA
10	Behenic acid C22:0	$C_{22}H_{44}O_2$	0.1	SAT
11	Nervonic acid C24:1	$C_{24}H_{46}O_2$	0.2	MUFA
	SAT		40.9	
	MUFA		13.8	
	PUFA		45.2	

Notes: SAT - Saturated; MUFA – Mono unsaturated; PUFA – Poly unsaturated

duration of storage. The transesterification provides conversion of these compounds into mono unsaturated fatty acids with a lesser saturated fatty acid and poly unsaturated fatty acid contents [45, 46].

3.5 Microwave-assisted transesterification

3.5.1 Statistical modelling fitting

The experimental and predicted RSM values are given in Table S2. Regression analysis was employed to correlate the influence of four MAT variables on the biodiesel yield by fitting the quadratic polynomial equation and it is shown in Eq. (5).

$$\begin{aligned}BY &= +96.48 + 1.85X_1 + 1.72X_2 \\ &-1.09X_3 - 0.146X_4 - 2.22X_1X_2 + 0.836X_1X_3 \\ &-2X_1X_4 - 0.461X_2X_3 + 1.12X_2X_4 + 1.53X_3X_4 \\ &-9X_1^2 - 8.78X_2^2 - 8.47X_3^2 - 4.84X_4^2 \ \ldots\end{aligned} \tag{5}$$

ANOVA (Table S3) provides F and P values allow to estimate how well the software-developed model fits the experimental values. The F value of 392.31 and P value < 0.0001 show that the developed model was highly significant. The individual performance evaluated by a linear effect such as oil to methanol ratio (X_1), catalyst concentration (X_2), and power (X_3) were also identified as significant with p-value < 0.05. The effect of interaction variables was determined between the oil to methanol ratio (X_1) and the time (X_4), with F value of 98.93, higher than that of the interaction between the oil to methanol ratio (X_1) and catalyst concentration (X_2), oil to methanol ratio (X_1) and power (X_3), catalyst concentration (X_2) and time (X_4), power (X_3) and time (X_4) with F value of 72.70, 10.31, 18.62 and 34.45, respectively (p-value < 0.5%). The quadratic effect of the volumetric ratio of oil to methanol (X_2) with F value of 197.69 (p-value < 0.0001) was found to be more than that of the catalyst concentration (183.82), power (171.27), and time (55.86) (Table S3). The lack of fit with P value of 0.0767 (> 0.05) non-significant term denotes that the selected combination of independent parameters was adequate for the developed model. The experimental regression coefficient (R^2) of 0.9973 represents the model adequacy. The predicted R^2 of 0.9920 is in agreement with that of the adjusted R^2 of 0.9947. A low coefficient of variance of 1.34 (<10%) shows the ratio of the estimated standard error to the mean value of the response [47, 48]. An adequate precision value of 52.45 indicates an adequate signal for the model. A signal-to-noise ratio higher than 4 is desirable and the present study value indicates that the prediction points of the developed model are within the design space [49].

3.5.2 Influence of process variables

The biodiesel yield is purely dependent on the number of triglycerides converted into FAME since the process variables are responsible for successful conversion. The interaction effect between the oil to methanol ratio and catalyst concentration is depicted in Fig. 3(a). It is found that the biodiesel yield gradually increased from 58 to 95% while increasing the oil to methanol ratio up to 1:7 and catalyst concentration up to 1 wt%. It could be due to the establishment of a contact surface area between the oil-alcoholic mixture and catalyst. Moreover, the transesterification process is reversible as sufficient oil to methanol ratio and catalyst concentration could maintain the forward reaction [50, 51]. Further increasing these variables, the yield was found to decrease significantly from 95 to 62%. During the transesterification process, when the oil to methanol ratio is increased above 7, it tends to create a mass transfer resistance between the different phases. Hence the solubility of the alcoholic solvent in oil tends to reduce which turns into a lower diffusion rate between the oil and methanol phases. Currently, the high catalyst concentration leads to soap formation. This emulsification endures the separation of FAME and glycerol [3, 52]. The effect of oil to methanol ratio and microwave power

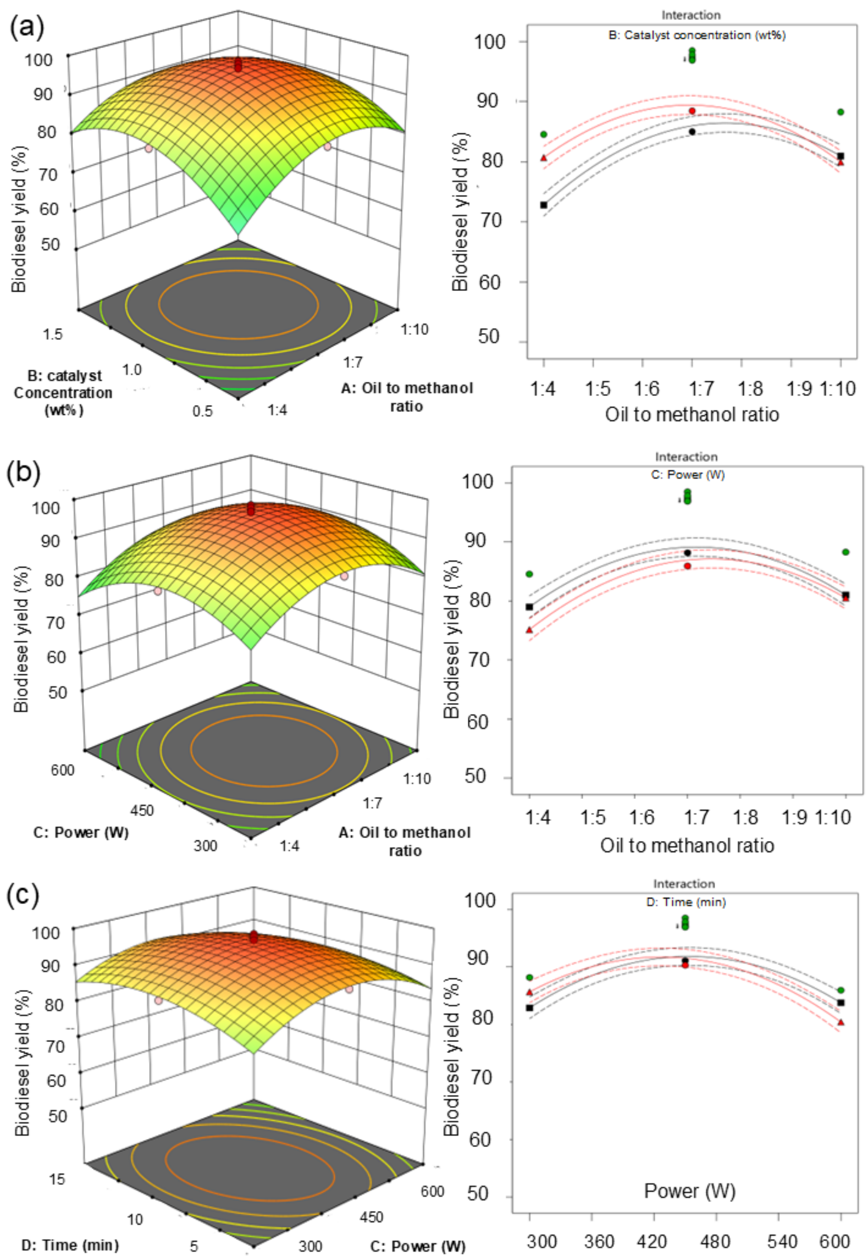

Fig. 3 Influence of MAT independent variables on biodiesel yield (%). (a) Biodiesel yield *vs.* catalyst concentration, oil to methanol ratio. (b) Biodiesel yield *vs.* power, oil to methanol ratio. (c) Biodiesel yield *vs.* time, power.

on biodiesel is depicted in Fig. 3(b). The molar ratio and microwave power are important MAT process variables. The yield elevated from 58 to 96% while the oil to methanol ratio (from 1:4 to 1:7) and microwave power (from 300 to 450 W) was increased. Due to the high dielectric constant and dipole rotation principle, methanol absorbs microwaves and enhances the temperature of the reaction which leads to a better transesterification process [53]. The higher level of power (beyond 450 W) and beyond the 1:7 oil to methanol ratio caused the lower yield. This might be a fact that at a higher molar ratio, the presence of methanol molecules could be very low. So, the absorbance of microwaves would be lower at high molar ratios. Subsequently, the supply of high power gives superfluous amounts of energy inside the reaction vessel that leads to the hydrolyzation of triacylglycerols into free fatty acids [54].

The biodiesel yield is varied by the interaction effect of microwave power and time significantly and it is displayed in Fig. 3(c). By enhancing the power from 300 to 450 W and increasing the time from 5 to 10 min, the yield is increased from 58 to 96%. Further increase beyond a certain time reduces the yield. Thus, the reaction time determines how much microwave energy can be supplied to the reaction. Generally, supply time can offer sufficient interaction between the microwaves and sample which yields a better transesterification process [55, 56]. When power and time exceed the limit (450 W and 10 min), it causes overheating inside the sample, thus leading to loss of methanol. This directly affects the molar ratio and the biodiesel yield gets declined [51, 54]. Also, the supply of microwaves over a long period results in higher soluble glycerol content and also the existence of unwanted by-products. The impact of MAT variables on the yield trend was similar to the previous studies of inedible olive oil transesterification using microwaves [51], microwave transesterification of papaya seed oil [50], palm oil transesterification by microwave [22] and *Ceiba pentandra* oil by microwave irradiation-assisted transesterification [11]. The experimental results of transesterification process were given in Supplement Table S3.

3.5.3 Optimization

A numerical regression model was employed to identify the MAT optimum condition for the production of biodiesel. The results were found with the maximum desirability (0.9667) of predicted biodiesel yield as 97.78%. The conditions were as follows: oil to methanol ratio – 7.2 (v/v%), catalyst concentration – 1 wt%, power – 445 W, and time – 9.8 min. At the optimum condition, the performance of the individual parameters on biodiesel yield and desirability is shown in Fig. 4. To evaluate the predicted optimum conditions, the experiments were triplicated (experiment conditions were slightly modified for operating purposes) and found the maximum biodiesel yield of 96.83 ± 0.45 % at the optimum condition of oil to methanol ratio – 1:7, catalyst concentration – 1 wt%, power – 450 W and time – 10 min. The obtained experimental values are in good agreement with the results obtained from the regression surface model.

3.6 Fuel characterization of biodiesel

The major fuel properties of produced BV diesel were determined and it is given in Table 4 [27–32, 36–39, 42]. The results are compared with biodiesel ASTM D6751-24 standard [42] and fossil diesel. Kinematic viscosity is the flow resistance property of the fuel and any fluids and it has a dynamic role in the fuel performance efficiency. This fact can be described by the higher viscosity of the fuel tending to reduced quality due to lower atomization, deposit formation in the engine, fouling, tubing blockage, and incomplete combustion [57]. The viscosity of the fuel inversely impacts the temperature, especially at a lower temperature the above-mentioned drawbacks exist. So, fuel that has high viscosity would not be preferable in cold regions [58]. The produced BV diesel's kinematic viscosity at 40 °C was found to be 4.4965 mm^2/s, it can be seen that it is significantly lower than the bio-oil (31.9250 mm^2/s), demonstrating that transesterification process was well performed at the optimized MAT conditions. Moreover, the BV biodiesel viscosity (4.4965 mm^2/s) lies within the limits of 1.9–6.0 mm^2/s (ASTM standards) and is also well in agreement with previous biodiesel production studies from various sources, such as *J. curcas* (4.723 mm^2/s), palm (4.6889 mm^2/s), soybean (4.3745 mm^2/s) and canola (4.5281) [59], *M. oleifera* (4.7658 mm^2/s) [2], and *C. pentandra* (4.69 mm^2/s) [11].

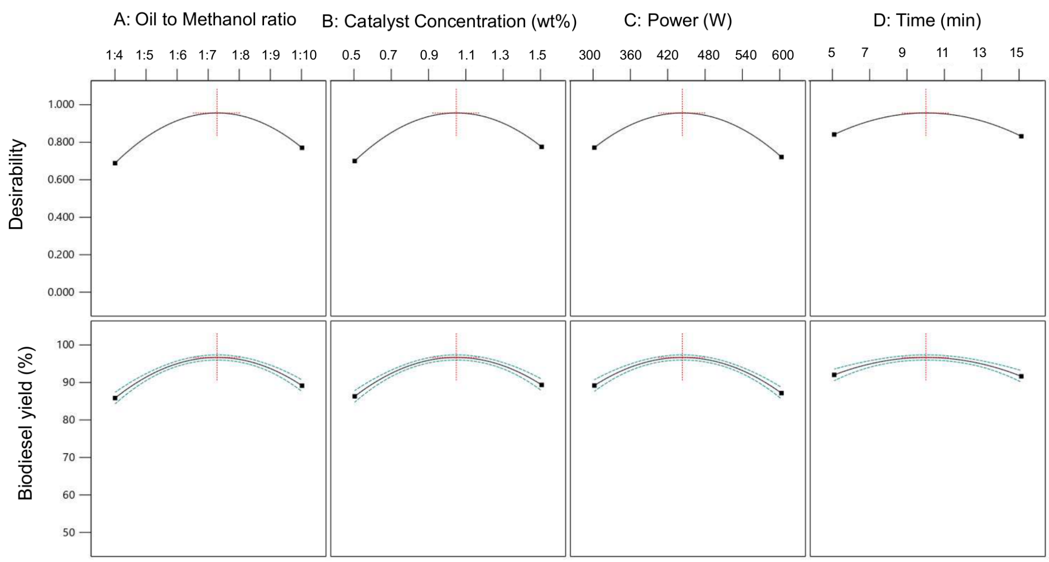

Fig. 4 Independent variables effect on optimum condition and its desirability

Table 4 The major fuel properties of BV biodiesel and comparison to the petrodiesel

Properties	Unit	Standard	BVO	BV biodiesel	Biodiesel ASTM D6751-24 [42]	Petrodiesel
Kinematic viscosity	mm^2/s	ASTM D445-24 [27]	31.92	4.49	1.9–6.0	3.11
Density	kg/m^3	ASTM D4052-22 [28]	904	871.34	870–900	834.6
Acid value	mg KOH/g	ASTM D1980-87(1998) [36]	1.3	0.2	0.8max	-
Free fatty acids	% mass	ASTM D5555-95(2023) [37]	0.65	-		-
Flash point	°C	ASTM D93-29 [29]	208	180	>130	58
Calorific value	MJ/kg	ASTM D240-25 [30]	38.5	39.99	-	45.68
Ash content	%	ASTM D874-23 [38]	0.01	-	0.05	-
Carbon residue	%	ASTM D4530-25 [39]	1.1	-	0.02	-
Cloud point	°C	ASTM D2500-23 [31]	5	3	−3 to 12	13
Pour point	°C	ASTM D97-17b(2022) [32]	7	2	−15 to 10	11

Density has a vital role in consuming the mass of fuel rather than combustion performance in the engine [60]. The density (at 15 °C) of BV biodiesel was found to be 871.3 kg/m^3, slightly higher than the 5% petrodiesel's density. High-density biodiesel enhances the volume and/or mass of fuel consumption as well as NO_x emissions [61]. Another important property is the consumption of fuels for required efficiency and it is highly dependent on the calorific value of the fuel. The calorific value of BV biodiesel was 39.996 MJ/kg when compared to petrodiesel (45.685 MJ/kg), it is slightly lower and it could be due to the presence of oxygen content in the biodiesel. Nevertheless, on a positive note, the presence of oxygen gives complete combustion of the biodiesel when using in diesel engines [2]. Another benefit of biodiesel fuel over petrodiesel is its high flash point. The flashpoint of fuel is a measure of its flammability; in safety concerns of handling and storage purposes, higher flash point fuel is preferable [59]. The flashpoint of the biodiesel produced in this study was 180°C, which is a good result considering the ASTM standard requires a flashpoint of a minimum of 130 °C. A high flashpoint, on the other hand, implies low volatility properties, which has a detrimental impact on diesel engine performance [62]. The cold flow parameters of cloud point (CP) and pour point (PP) can be used to assess the behavior of biodiesel during cold seasons. The temperature at which the small lump of crystals is formed visibly when fuel is allowed to cool is known as cloud point and on further enhancing the cooling temperature, the fuel becomes gel which loses its flowability that is called as pour point [63]. BV biodiesel demonstrated significant cold flow characteristics in this investigation. The temperatures of CP and PP were found to be 3 and 2 °C, respectively. The lower CP and PP values in the BV biodiesel indicate the presence of lower paraffin content.

3.7 Fuel characterization of biodiesel-diesel blends

As previously stated, biodiesel had higher volatility, density, and viscosity as well as a lower heating value, when compared to petrodiesel. Blending biodiesel with petrodiesel fuel enhances the characteristics of the fuel while also reducing environmental pollution [64]. During the preparation of biodiesel–diesel blends, the mixtures were thoroughly stirred to ensure uniform mixing, and no phase separation was observed under laboratory conditions. The prepared blends characterized by their biodiesel content and remained visually homogeneous and stable during the storage and testing period. The physicochemical parameters of nine biodiesel blends from 10 v/v% (B10) to 90 v/v% (B90) were compared to diesel fuel and it is shown in Fig. 5(a)–(f). The fuel characteristics of BV biodiesel improved dramatically as the increment in percentage of petrodiesel. From Fig. 5(a), the lower number of blends (B10 and B20) exhibited kinematic viscosities (3.2 and 3.3 mm^2/s) very close agreement to the petrodiesel (3.1135 mm^2/s). It was noted that, while the blending ratio was increased, there was not a huge change between the density of petrodiesel and biodiesel (Fig. 5(b)). However, densities of B10 and B20 (838.07 and 841.04 kg/cm^3) were close to the density of the petrodiesel (834.6 kg/cm^3). The biodiesel calorific value was significantly raised by increasing the diesel fraction in the mix due to the lowering of oxygen concentration, as shown in Fig. 5(c) [26, 65]. B10 and B20 had calorific values of 45.1257 and 44.5664 MJ/kg, respectively, which were extremely adjacent to the petrodiesel (45.685 MJ/kg). Even a minor fraction of diesel fuel resulted in a significant drop in the flashpoint of the BV biodiesel, as seen in Fig. 5(d).

Furthermore, B10, B20 had flashpoints in the range of 69–82 °C slightly higher than the flashpoint of the petrodiesel (58 °C). However, fuels with flashpoints more than 66 °C are supposed to be safe to handle and lower

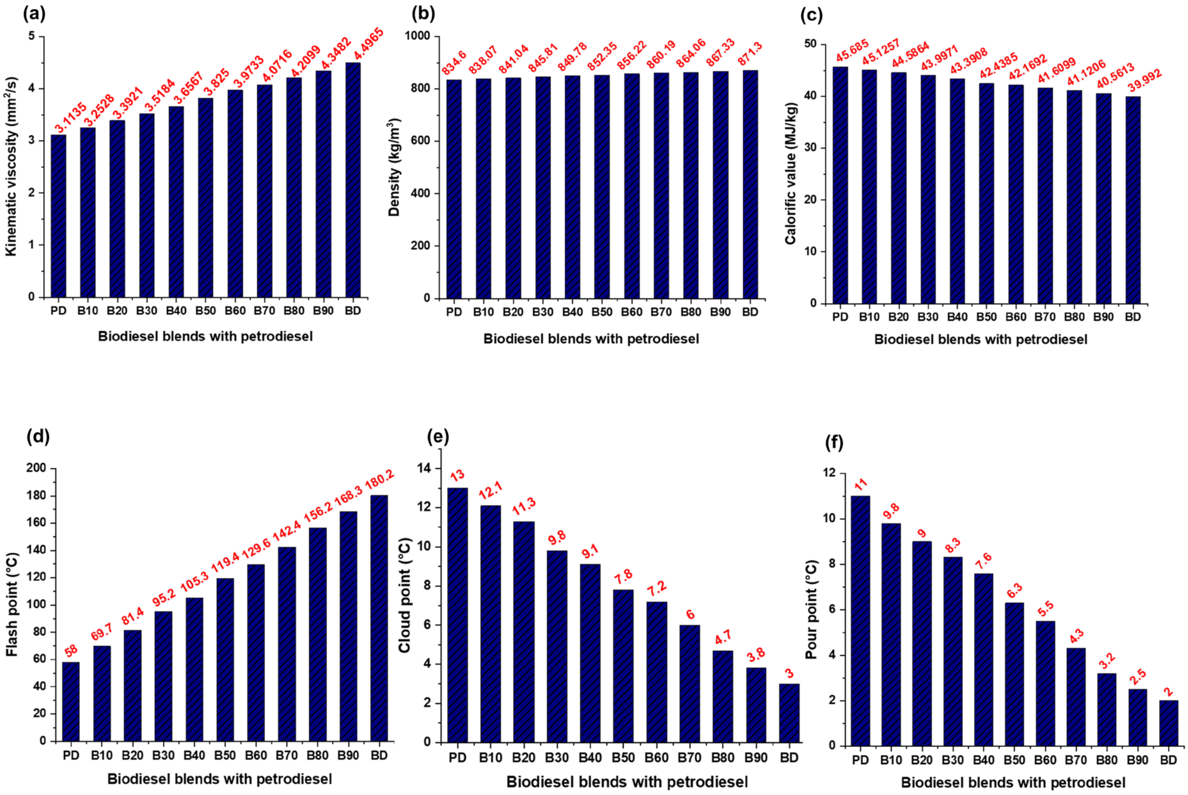

Fig. 5 The physicochemical parameters of biodiesel and its blends: (a) kinematic viscosity *vs.* BV blend with petrodiesel, (b) density *vs.* BV blend with petrodiesel, (c) calorific value *vs.* BV blend with petrodiesel, (d) flash point *vs.* BV blend with petrodiesel, (e) cloud point *vs.* BV blend with petrodiesel, (f) pour point *vs.* BV blend with petrodiesel. B10 to B90 is v/v% blended with petrodiesel and biodiesel blended ranges.

hazardous flammability prospects [66]. The cold properties such as cloud and point with blends are shown in Figs. 5(e) and 5(f) respectively. The cold properties of the fuel are mainly depending on the presence of saturated hydrocarbons. Petroleum-derived diesel is typically made up of majorly saturated hydrocarbons (about 75 v/v%), mostly paraffin like n-, iso-, and cycloparaffin, and aromatics (about 25%) including alkylbenzenes and naphthalene [67–69]. The difference could be in the present study where the lower values of CP and PP of BV biodiesel show that it could have a lesser number of saturated hydrocarbons and it implies the blended fuel properties as well. Moreover, the lesser CP and PP value of blended fuels would be beneficial to use in cold regions. The similar study was carried out by Soudagar et al. [70], the Mahua biodiesel was blended at various concentration about 20% and 30%, with petrodiesel and analysed the physicochemical properties such as., kinematic viscosity, pour point, cloud point and flash point. The similar trend was observed when compared to the present study. In addition to that biodiesel from waste cooking oils [71, 72], also representing similar performance on the fuel physicochemical properties in different dosage level blending with petrodiesel.

3.8 Energy consumption

The energy balance of the microwave-assisted transesterification process was estimated based on the applied microwave power (450 W) and reaction time (10 min), corresponding to an energy input of approximately 0.27 MJ. Considering the calorific value of the produced biodiesel (39.992 MJ/kg), the energy output from the obtained biodiesel was estimated to be approximately 3.37 MJ, demonstrating a favorable energy balance for the process.

4 Conclusion

The present research work, comprehensively studied the extraction of oil from *Bauhinia variegate* seeds, their properties, production of biodiesel via transesterification process using MAT, interaction effects of MAT variables of biodiesel yield, properties of biodiesel and biodiesel blended petrodiesel. The following conclusions are drawn from the experimental data:

- *Bauhinia variegate* seeds can produce a significant amount of oil (32.43%), its fatty acid compositions, presence of functional groups, also its physicochemical properties show the potential to produce biodiesel. Especially lower acid value (1.30 mg KOH/g oil) (less than 2) gives a direct approach to the transesterification process.

- Microwave-assisted transesterification was employed to produce biodiesel from BVO. The optimization was carried out using RSM, at the optimum condition of oil to methanol ratio 7 (v/v), 1 wt% catalyst concentration, 450 W power and a shorter time of 10 min the biodiesel yield was found to be 96.83 ± 0.45%. The obtained BV biodiesel was characterized and found that the important properties, such as density, kinematic viscosity, flash point, calorific value, cloud and pour point, lie within the ASTM D6751-24 standard [42] permissible limits.
- From the overall experimental results, it can be determined that utilizing 1 kg BV seeds can produce 324.32 g oil and 314.01 g of its biodiesel.
- Petrodiesel with *Bauhinia variegate* biodiesel blend was carried out and their physicochemical properties were analyzed. It was found that up to 20% biodiesel blending gives close results with petrodiesel properties.
- Summarizing the above points, the microwave-assisted transesterification process was found to be efficient for BV biodiesel production. This beneficial approach leads to reducing the production cost of biodiesel in a continuous mode. However, still, there is a research gap available to implement an industrial-scale microwave reactor for continuous bulk operations.
- Prior to the commercialization of biodiesel production using the microwave technique, a detailed environmental and economic investigation is required, and future research should focus on:
  1. Development of microwave reactors in a loop for continuous operation;
  2. Employing multi-stage microwaves with higher capacity rather than single-stage;
  3. Combining microwave with some other intensive process technique.

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